N84-25830

NASA Technical Memorandum 83670

Deposition Stress Effects on Thermal Barrier Coating Burner Rig Life

James W. Watson
Northwestern University
Evanston, Illinois

and

Stanley R. Levine
Lewis Research Center
Cleveland, Ohio

Prepared for the
Eleventh International Conference on Metallurgical Coatings
sponsored by the American Vacuum Society
San Diego, California, April 9-13, 1984

NASA

DEPOSITION STRESS EFFECTS ON THERMAL BARRIER COATING BURNER RIG LIFE

James W. Watson
Northwestern University
Department of Materials Science
Evanston, Illinois

and

Stanley R. Levine
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-2113

SUMMARY

A study of the effect of plasma spray processing parameters on the life of a two layer thermal barrier coating was conducted. The ceramic layer was plasma sprayed at plasma arc currents of 900 and 600 amps onto uncooled tubes, cooled tubes, and solid bars of Waspalloy in a lathe with 1 or 8 passes of the plasma gun. These processing changes affected the residual stress state of the coating. When the specimens were tested in a Mach 0.3 cyclic burner rig at 1130° C, a wide range of coating lives resulted. Processing factors which reduced the residual stress state in the coating, such as reduced plasma temperature and increased heat dissipation, significantly increased coating life.

INTRODUCTION

The trend in gas turbine technology has been to increase operating temperature and hence improve power and efficiency. Higher temperatures have increased engine durability problems through increased creep and oxidation rates.[1,2] Thermal barrier coating systems represent a promising means of allowing hotter, more efficient engines without sacrificing engine life.[1-5] Thermal barrier coating systems consist of an insulating ceramic layer on top of a metallic bond layer. The ceramic insulates the cooled components, thereby reducing metal temperature and hence creep and oxidation rates.[1,6] The bond coat prevents oxidation of the substrate as well as being essential for adhesion of the ceramic.[7]

A major problem with thermal barrier coatings is spalling of the ceramic layer.[3,4,6,8,9] Evidence that oxidation is a necessary condition for ceramic spallation in a burner rig environment has been presented.[9] In a gas turbine, higher start-up and shut-down thermal stresses may be a contributing factor.[1,2,10,11] Transient and steady state stresses arise due to thermal gradients through the coating and the thermal expansion mismatch between the ceramic coating and the superalloy substrate. Stresses also arise from the coating deposition process and thermal history. Thermal history generated stresses arise from bond coat oxidation and inelastic processes occurring in the bond coat and ceramic. Sintering and phase changes also contribute stresses due to volume changes.[9] Coating life is dependent on the net effect of these difficult to separate factors. More directly, prior studies have related coating life to the composition and oxidation behavior of the bond

coat,[2,9-13] the composition of the ceramic coat,[2,12,14] the duration of thermal cycles,[9-11] and the application technique.[3,11,14-16] Plasma spraying is the most common application technique for thermal barrier coatings. There are several parameters within the plasma spraying process that control the character of the coating produced. Among these are the plasma arc current (plasma temperature), substrate cooling, and the speed of spraying. This study relates these parameters to the microstructure, the residual stress state, and finally, to the life of the coating in cyclic burner rig tests.

EXPERIMENTAL PROCEDURES

Materials and Processing

Waspalloy (γ - γ' superalloy with a nominal composition* of Ni-19Cr-14Co-4.3 Mo-3Al-3Ti) cylindrical specimens were plasma sprayed with a two-layer thermal barrier coating.[1,5] The thermal barrier coating consisted of a NiCrAlY bond coat and an yttria partially stabilized zirconia ceramic coat.[4] The bond coat composition was Ni-14.2Cr-14.5Al-0.3Y and its thickness was 0.1 mm.[6,8] A ZrO_2-$8Y_2O_3$ ceramic coat, 0.44 mm thick was used.[4] The coating was applied with the plasma gun attached to the traversing apron of a thread-cutting lathe. The bond coat was applied in two passes at 450 amps (plasma arc current). The arc gas was a mixture of Ar + 4 vol% H_2 and the stand-off was 12.8 cm.[7,10] The parameters used to apply the ceramic coat varied between specimens. Three types of specimens were used; hollow tubes with no cooling air, hollow tubes with internal forced 20° C air-cooling, and solid bars. The coatings were applied with either 1 or 8 passes of the plasma gun. The rotational speed of the lathe and the traverse speed of the gun were adjusted to accomplish coating application in about 2 min regardless of the number of passes (75 rpm and 5.5 cm/min for 1 pass, 300 rpm and 50 cm/min for 8 passes.) Plasma arc currents of 900 and 600 amps were used with Ar arc gas and 7.7 cm stand-off. The specimens and spraying conditions are summarized in Table I. At a later date a set of thermocoupled specimens were coated. Sheathed chromel-alumel thermocouples were brazed into a longitudinal groove cut in the surface of each specimen. The thermocouple signal was channeled through a slip ring to a millivolt recorder.

Burner Rig Tests

Specimens were tested in a Mach 0.3 burner rig firing Jet A-1 fuel. The test cycle was 60 min in the flame followed by 3 min of forced air cooling.[9,10] The specimen temperature, as measured with an optical pyrometer and applying a cell window correction of 20° C and an emissivity correction of 75° C, was 1130° C. Once in the flame, the specimens took about 3 min to reach equilibrium temperature. Eight specimens were mounted in a 500 rpm rotating fixture, 5.5 cm from the burner nozzle. As individual specimens failed, they were replaced with fresh ones. Failure was considered to have occurred when sections of ceramic had spalled. Specimens were checked after every cycle for the first ten cycles and then at least once every 15 cycles.

*All compositions are wt.%.

Microscopy

Representative ceramic coatings were examined in a scanning electron microscope (SEM) using the fracture profile technique. Other tested specimens were mounted and polished for optical microscopy in order to determine the extent of bond coat oxidation and the appearance and location of the fracture path.

RESULTS

Burner Rig Tests

The results of the burner rig tests are summarized in Table II and Fig. 1. Lives ranged from 0 cycles to 207 cycles. Zero cycle failures occurred when the stresses developed upon cooling after spraying caused the coating to spall. These failures occurred only with coatings applied at 900 amps in 1 pass to both uncooled and air-cooled tubes. The coatings that latest longest were those applied at 600 amps in 8 passes to the air-cooled hollow substrates. For any set of parameters, 600 amp coatings outlasted their 900 amp counterparts, by a factor of at least 1.7. In all cases the 8-pass coatings lasted longer than the similar 1-pass coating. The degree of improvement in coating life achieved by going from 1 pass to 8 passes varied widely with the different substrates; on air-cooled substrates coating life improved by a factor of nearly 20 while with the solid substrate coating life improved by a factor of only 1.2. The substrate which produced the most durable coating was not the same for the 1-pass and 8-pass groups of specimens. With the 1-pass coatings the solid bar produced the best coating while among the 8-pass coatings the most durable was that applied to the air-cooled tube.

In several instances gross spalling was observed upon heating within 15 sec of the specimens moving into the burner rig flame. This probably was due to prior failure by delamination on cooling from a prior exposure.[9] Failure always occurred at the bond coat/ceramic coat interface. Remaining on the bond coat was the usual thin discontinuous layer of zirconia (figs. 2(a), (b), and 4(b). The severity of failure was very dependent on whether 1 or 8 passes were used in spraying. With the exception of the 900 amp, uncooled specimens, the 8-pass coatings spalled over only a small area (fig. 2(a)), while the 1 pass coatings spalled over a much larger area (fig. 2(b)). Coatings applied at 900 amps to uncooled specimens showed a difference in the severity of failure; the 8-pass coating spalled over a large area similar to the failure shown in Fig. 2(b) while the 900 amp 1-pass coating spalled over virtually the entire specimen and almost always upon cooling after coating application.

Microscopy

SEM examination revealed that the various coatings had very similar microstructural features. Also, there was no significant difference between as sprayed and after-test fracture profile microstructures. The microstructure of any particular coating varied widely across the coating. Several of the characteristic features are noted in Fig. 3(a); porosity (A), microcracking (B), unmelted or splattered particles (C), columnar regions (D), and structural discontinuities between splats (E). Any given coating would have, for example, regions of extensive columnar growth and other regions of virtually none

(fig. 3(b)). This observation was true of the other microstructural features as well.

With the exception of the 1-pass coating applied to the uncooled tube, the 900 amp group of coatings was very similar. Neither the number of passes nor the type of substrate produced any noticeable microstructural differences. All the coatings had porosity in the form of nearly round pores (fig. 3(b)). These ranged in size from less than 1 μm to nearly 10 μm. During spalling, cracks must run from near the substrate to the outer surface. In all but the 1-pass coatings on uncooled substrates, these cracks seemed to do so in a stepping mechanism; propagating part-way through the coating, then running parallel to the substrate along a splat boundary, finally continuing through the coating. This mechanism reveals the profiles of certain splats and the tops of others (fig. 3(a)).

The 900 amp coating on the uncooled tube had the most uniform structure and the fewest structural discontinuities (fig. 3(c)). There was, however, extensive randomly oriented microcracking. Figure 3 shows a major crack running parallel to the substrate, but it did not appear to lead to failure. However, it does demonstrate the high residual stress level in this short-lived coating. The failure path did not follow the stepping mechanism. Instead cracks seemed to slice through the entire coating in one plane without revealing the tops of any splats.

The 600 amp group of coatings was very similar and closely resembled the majority of 900 amp coatings. The same microstructural features as in Fig. 3(a) can be found in Fig. 3(d). The failure path in the 600 amp coatings propagated via a stepping mechanism similar to the majority of 900 amp specimens (fig. 3(d)). The columnar growths in the 600 amp coatings tended to be smaller than those in the 900 amp coatings.

Optical microscopy of the as-sprayed specimens showed some bond coat oxidation. This is typical of bond coatings sprayed in air. This oxidation appeared as stringers along splat boundaries (fig. 4(a)) which grew with exposure (fig. 4(b)). Given similar lifetimes, 600 and 900 amp ceramic coated specimens exhibited similar bond coat oxidation. Microstructurally, the oxidation was very consistent with that reported in the literature.[7,9,10,13]

DISCUSSION

A wide range of coating lives resulted from the variations of plasma spraying parameters. The variety of spraying parameters had an effect on the microstructure of the coatings as evidenced by changes in density as noted elsewhere,[15] and columnar growth, fracture path and bonding between splats. Inseparable from microstructural effects are residual stress effects resulting from processing. The residual stress state of the coating after deposition is controlled by the plasma and substrate temperatures during spraying, by the thermal expansion mismatch between the coating and substrate, and by solidification and stress relief processes in the ceramic. The higher thermal expansion coefficient of the substrate relative to that of the zirconia produces a compressive residual stress in the coating. As the plasma temperature and the substrate temperature are increased the amount of contraction mismatch upon cooling increases producing greater compressive residual stress levels in the ceramic. Residual stresses, when added to thermal gradient and transient

stresses, and the stresses that arise from time dependent phenomena such as bond coat oxidation and creep[9] cause crack propagation and eventual ceramic spalling. Microstructure controls the ability of the ceramic to accommodate stress.[14] Thus initial residual stress and microstructure are very critical in determining coating life as revealed by the results of this study.

A key factor in the coating residual stress picture is substrate temperature. A plot of coating lives versus maximum measured metal temperature during coating deposition is given in Fig. 5. A plot of $\Delta\alpha(T) \cdot (T_{max} - T_{ambient})$ is very similar. For any substrate/cooling configuration, 600 amp coatings lasted longer than 900 amp coatings. This is inconsistent with other results.[16] With other factors equal, coatings applied in 8-passes always lasted longer than those applied in one-pass. Lower power, more passes, cooling, and high substrate thermal mass tend to reduce residual stress. The fact that a single correlation between temperature and life was not obtained indicates that substrate thermal mass and cooling are important considerations that have a strong effect on ceramic coating build-up stress via solidification and stress relief processes. However, for a given configuration, life followed a linear relation with substrate temperature.

CONCLUDING REMARKS

The cyclic burner rig testing of specimens coated with ZrO_2-8 Y_2O_3/NiCrAlY under a variety of ceramic plasma spraying conditions revealed several processing trends having a significant bearing on coating life. Lowering the heat input to the specimen by reducing the plasma spray power level considerably increased coating life. Improving the ability of the substrate to dissipate heat, by using solid bars or air-cooling also significantly improved coating life. Finally, coating life was increased by increasing the time span during which heat is put into the specimen at any single location by increasing the number of passes. From the results and qualitative thermal stress considerations, it was inferred that these processing procedures reduced ceramic coating compressive residual stresses resulting from ceramic application.

REFERENCES

1. S. J. Grisaffe, S. R. Levine, and J. S. Clark, NASA TM-78848, 1978.

2. S. Stecura, Am. Ceram. Soc. Bull., 61, 256, (1982).

3. I. E. Sumner and D. L. Ruckle, NASA TM-81512, 1980.

4. S. Stecura, NASA TM X-3425, 1976.

5. S. R. Levine, R. A. Miller, and S. Stecura, in High Temperature Corrosion, NACE-6, edited by Robert A. Rapp (National Association of Corrosion Engineers, Houston, TX, 1983), pp. 621-627.

6. J. W. Vogan, L. Hsu, and A. R. Stetson, Thin Solid Films 84, 75 (1981).

7. M. A. Gedwill, DOE/NASA/2593-18, NASA TM-81567, 1980.

8. R. McPherson, Thin Solid Films 83, 297 (1981).

9. R. A. Miller and C. E. Lowell, Thin Solid Films 95, 265 (1982).

10. M. A. Gedwill, NASA TM-81684, 1981.

11. G. McDonald and R. C. Hendricks, Thin Solid Films 73, 491 (1980).

12. S. Stecura, NASA TM-78976, 1978.

13. S. Stecura, NASA TM-79206, 1979.

14. A. S. Grot and J. K. Martyn, Am. Ceram. Soc. Bull., 60, 807 (1981).

15. S. Stecura, NASA TM-81724, 1981.

16. R. C. Hendricks and G. McDonald, NASA TM-82795, 1982.

TABLE I. - TEST SPECIMENS AND SPRAY CONDITIONS

Bond Coat: Ni-14.2Cr-14.5Al-0.3Y, 0.01 cm thick, 450 amps, Ar-4 vol % H_2 arc gas, 2-passes, 12.8 cm stand-off

Ceramic Coat: ZrO_2-$8Y_2O_3$, 0.044 cm thick, Ar arc gas, 7.7 cm stand-off

Coating procedure and specimen configuration	900 amps	600 amps
1 pass, hollow tube, cooling air	6 specimens	3 specimens
8 passes, hollow tube, cooling air	6	3
1 pass, hollow tube, no cooling air	6 specimens	3 specimens
8 passes, hollow tube, no cooling air	6	3
1 pass, solid bar	5 specimens	3 specimens
8 passes, solid bar	6	3

TABLE II. - BURNER RIG TEST LIVES

Cycle: 60 min heating to 1130° C, 3 min cooling

	Passes	Plasma arc current			
		900 amps		600 amps	
		Lives Hours (cycles)	Average life	Lives Hours (cycles)	Average life
Uncooled tubes	1	0,0,0,0,0,1	0.2	2,3,3	2.6
	8	5,5,6,6,6,7	5.8	52,72,123	82.3
Air-cooled tubes	1	0,1,2,3,5,6	3.5	5,6,6	5.7
	8	63,70,71,76,87,86	75.5	158,197,207	187.3
Solid bars	1	26,29,31,31,35	30.4	62,107,130	99.7
	8	31,40,44,51,58,62	47.7	78,94,152	108.0

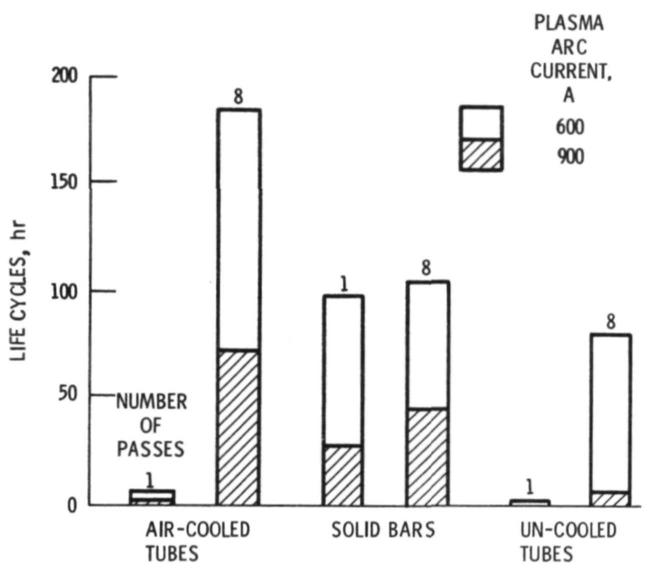
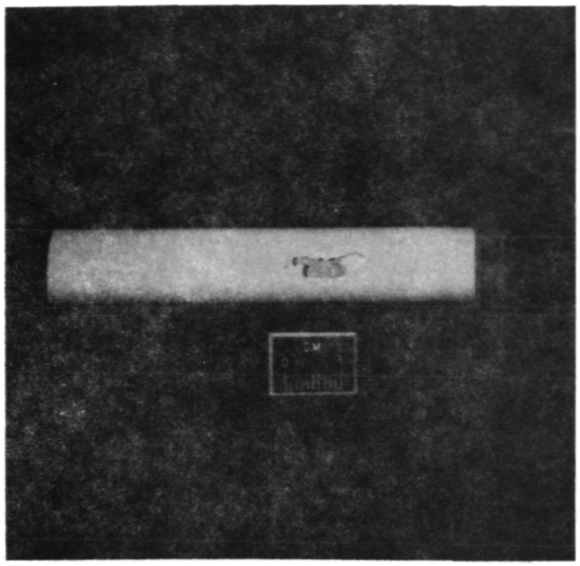
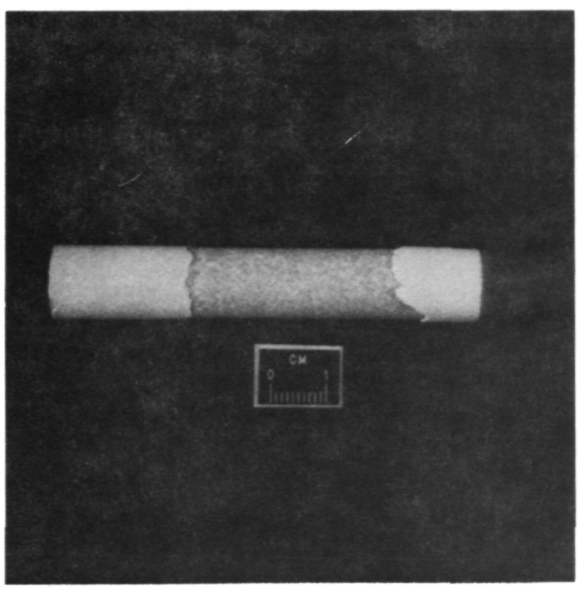


Figure 1. - Effects of process variations on ZrO_2-$8Y_2O_3$/NiCrAlY coating life.

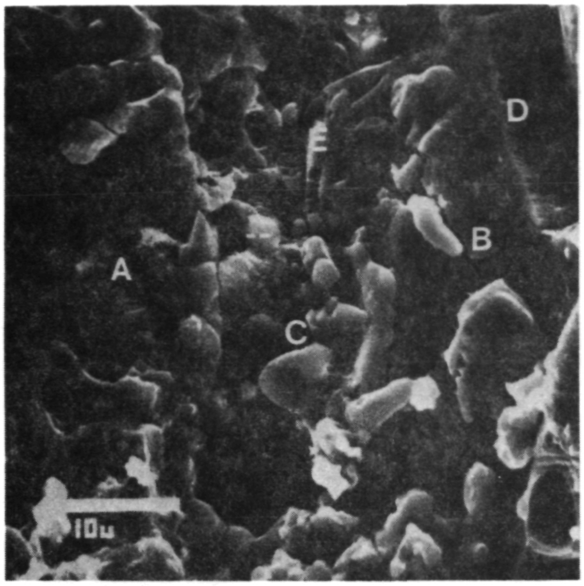


(a) 8-pass, 900 A, air-cooled tube.

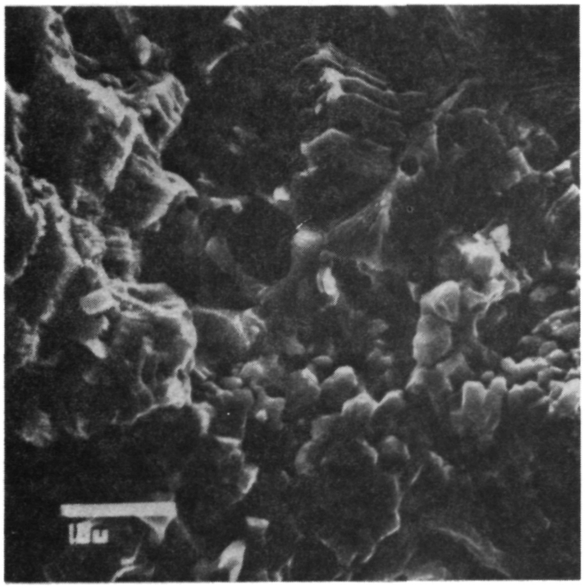


(b) 1-pass, 900 A, air-cooled tube.

Figure 2. - Two failure macrostructures were obtained: (a) limited spalling with most 8-pass coatings, and (b) massive spalling with 1-pass coatings and the 8-pass, 900 amp, coatings on un-cooled tubes.

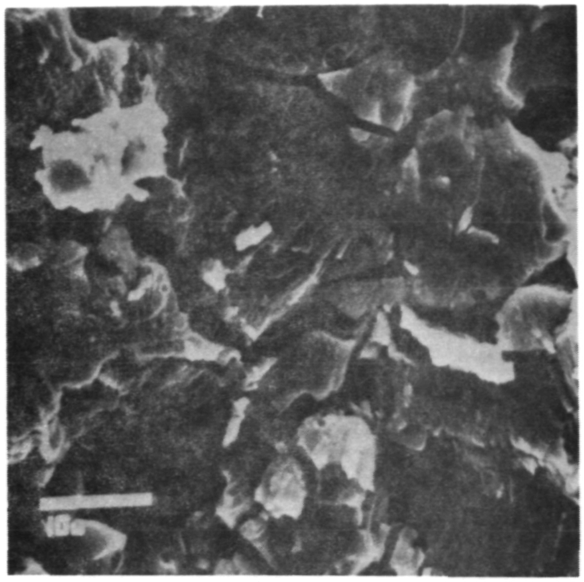


(a) 8-pass, 900 A, air-cooled tube.

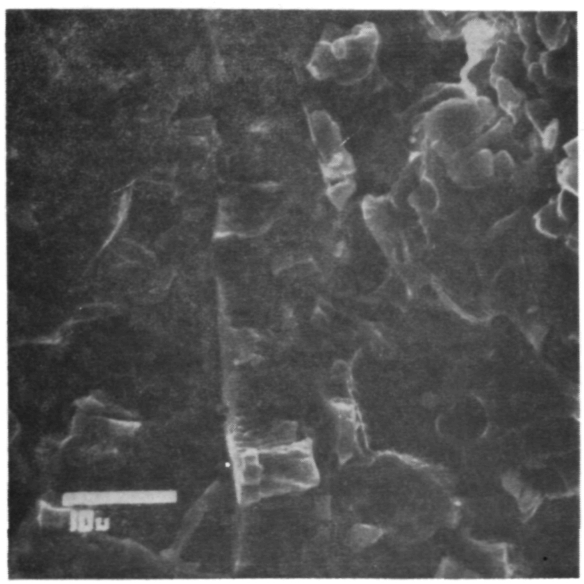


(b) 1-pass, 900 A, solid bar.

Figure 3. - Typical ceramic coatings SEM fractographs. Features called out in (a) are: A-porosity, B-microcracking, C-unmelted or splattered particles, D-columnar growth, and E-structural discontinuity between splats. All coatings had regions of columnar and non-columnar growth (b). The coating in (c) was most uniform. The fracture path running alternately between and through splats is clearly illustrated in (d).

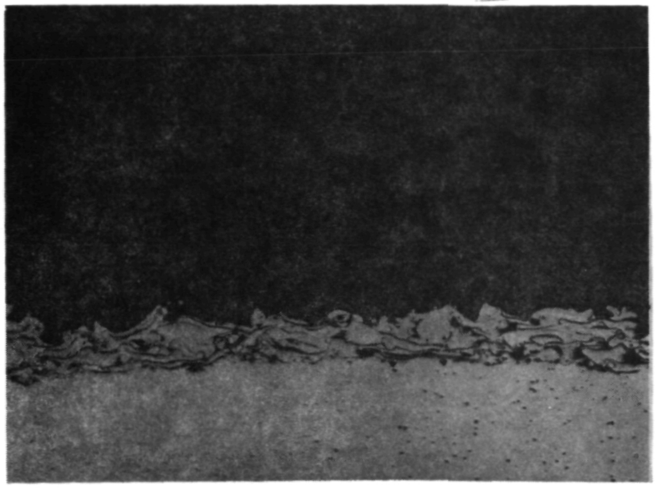


(c) 1-pass, 900 A, un-cooled tube.

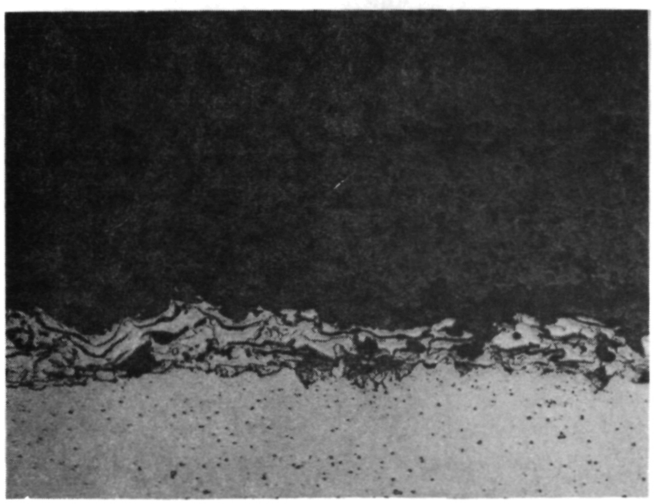


(d) 1-pass, 600 A, un-cooled tube.

Figure 3. - Concluded.



(a) As coated.



(b) After 87 1-hr cycles to 1130° C.

Figure 4. - Typical coating microstructure as exemplified by 8-pass, 900 amp coating on an air-cooled tube (a) before and (b) after test.

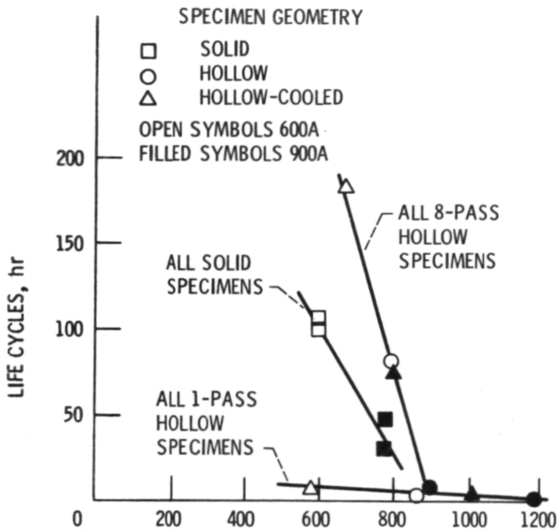


Figure 5. - Effect of substrate temperature on ZrO_2-$8Y_2O_3$/NiCrAlY coating life.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-83670		

4. Title and Subtitle	5. Report Date
Deposition Stress Effects on Thermal Barrier Coating Burner Rig Life	
	6. Performing Organization Code 505-33-1A
7. Author(s) James W. Watson and Stanley R. Levine	8. Performing Organization Report No. E-2113
	10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

James W. Watson, Northwestern University, Dept. of Materials Science, Evanston, Illinois; Stanley R. Levine, Lewis Research Center. Prepared for the Eleventh International Conference on Metallurgical Coatings sponsored by the American Vacuum Society, San Diego, California, April 9-13, 1984.

16. Abstract

A study of the effect of plasma spray processing parameters on the life of a two layer thermal barrier coating was conducted. The ceramic layer was plasma sprayed at plasma arc currents of 900 and 600 amps onto uncooled tubes, cooled tubes, and solid bars of Waspalloy in a lathe with 1 or 8 passes of the plasma gun. These processing changes affected the residual stress state of the coating. When the specimens were tested in a Mach 0.3 cyclic burner rig at 1130^{0} C, a wide range of coating lives resulted. Processing factors which reduced the residual stress state in the coating, such as reduced plasma temperature and increased heat dissipation, significantly increased coating life.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Ceramic coating Zirconia Processing Plasma spray	Unclassified - unlimited STAR Category 27

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

SPECIAL FOURTH CLASS MAIL
BOOK

U.S. MAIL

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

NASA

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Return